1975

Instructor's Guide to the THERMAL PHYSICS Module Cluster of the Physical Science Modules for Bioscience Students Project

INSTRUCTOR'S GUIDE TO THE

THERMAL PHYSICS

MODULE CLUSTER

of the

Physical Science Modules for Bioscience Students Project

Consisting of three modules:

1. THERMOMETRY AND HEAT TRANSPORT IN THE HUMAN BODY
2. FUNDAMENTAL ENERGY PROCESSES OF THE HUMAN BODY
3. THERMAL REGULATION OF THE HUMAN BODY

For use in the following modes:

- students in an introductory, non-calculus physics, in class or outside class
- former students of such a course, for independent study
- instructors of physics wishing to learn of biological applications of physics

CONTENTS OF THIS GUIDE

INTRODUCTORY

These instructional materials are produced as part of a study of bioscience applications in physics and manners of presenting them to interested students and instructors. You will aid this endeavor greatly if you try using these materials in one of the three use modes listed on the cover sheet of this guide, and by reporting your (and students') results in the appropriate questionnaire. It would also be useful to us for you to critically annotate the study materials as you (and students) read them (write on the document), and return these to the project office. Duplicate, fresh materials can be sent to you by return mail if you (or students) wish to have a reference copy for yourselves.

Notice that the manner of presentation of the material, as well as the content, is part of the study. Therefore, comments on and reactions to either content or pedagogy are desired.

If time permits, those making serious attempts to use these materials as instructional aids will be furnished with a supplement to this guide in the form of a revision, pointing out troublesome matters of pedagogy or content that have come to our attention from other users, as well as bugs that have been uncovered in the laboratory equipment or exercises. It is hoped thereby to overcome some (understandable) instructor reluctance to try materials in the development stage. It should be pointed out, however, at the outset that a considerable amount of testing has already gone into these materials, and we believe them to be quite useable as they are now.

I. Theme of the cluster: Thermal Physics

These modules teach energy conservation, thermal energy, heat flow, and feedback systems in the contexts of energy management and temperature regulation of the human body. The three component modules are somewhat redundant in their topical content and can roughly be distinguished by their entry level requirements: (1) THERMOMETRY . . . is intended for students who have studied some thermal physics; (2) FUNDAMENTAL . . . is intended for students currently studying thermal physics or those having previously studied and wishing a refresher of principles in the biological context; (3) THERMAL . . . is intended as a pure applications exercise of thermal physics and includes a rudimentary introduction to the principles of feedback systems.

The format of each module is designed around the so-called "learning cycle" devised by Robert Karplus (Science Teaching and the Development of Reasoning; a workshop manual available from Lawrence Hall of Science, Berkeley, California 94720; specify physics). This format consists of three sections:

Exploration: some memory joggling, rhetorical questioning, and some laboratory exercises designed to provide a basis in concrete experience for the abstractions which are the physical laws.

Invention: a gradual organization and generalization of the previous experimental data around the conventional physical laws.

Applications: a set of tasks, partly written, partly experimental, which require the interpretation of the physical laws in new contexts or the exploration of new implications.

The goal of this design is to provide the student with self-contained instructional packets, each of which might occupy about a week's worth of supplemental work, or one lecture plus somewhat less outside work. The (preliminary) exploration activities in the laboratory are designed so that they can be done in an unsupervised environment, at the student's convenience. The invention activity is done as more or less conventional study and problem solving work outside of class, or in lecture. The (final) applications activities in the laboratory are more demanding and might best be done as a substitute for and in the environment of a conventional laboratory session.

Obviously there are potential problem areas in trying to match the anticipated instructional needs of prospective students and instructors to the actual requirements (and temperament) of any one individual. We, the designers of this project, wish to benefit from the experiences of instructors and student-users to the extent that we may design future modules which better make these matches than do the existing ones.

In general, we are interested in examining the acceptance of modules by faculty and students. We wish to characterize, if possible, particular problems which modular materials present to students and to instructors. We wish, further, to evaluate the suitability of the topics and the reasoning/problem-solving skills which we have written into these modules as intended learning outcomes.

For these purposes, questionnaires for both instructors and student-users are provided at the end of this GUIDE where they may be readily torn off and mailed. We ask the receiver of these modules to take the time to fill out and return the instructor's questionnaire for our own analysis, even if (s)he does not actually employ the modules per se with students.

THEME : TEMPERATURE REGULATION OF THE BODY

PHYSICAL PRINCIPLES EMPLOYED

1. Thermal Energy
2. Heat Processes
3. Energy Conservation
4. Feedback Systems

Figure 1: Fundamental physical principles required for a discussion of the body's temperature regulation.

THERMAL PHYSICS CLUSTER

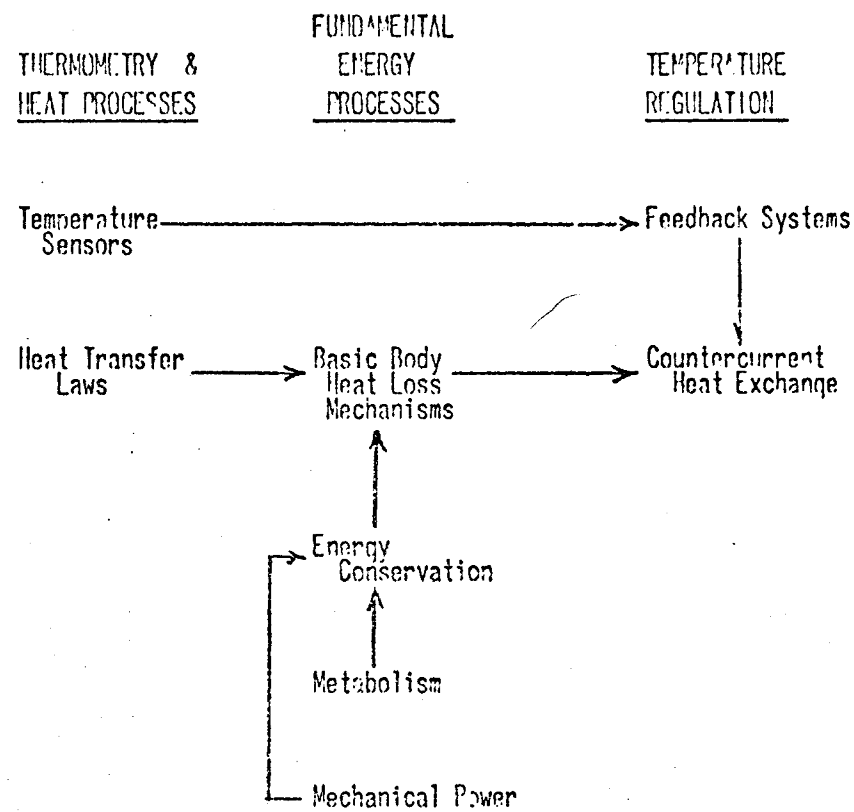


Figure 2: Interrelations among parts and principles of the thermal physics cluster.

II. Contents

The topical organization of the cluster and of the three individual modules within that cluster is displayed in the accompanying figures 1 and 2. A more detailed list of contents for each module appears below amplified by brief descriptions of pertinent sections.

1. THERMOMETRY AND HEAT TRANSPORT IN THE HUMAN BODY

Prerequisites

1. Distinguish between the terms "thermal energy" and "temperature" by providing a written explanation of what each term represents, by providing a basic example which illustrates your explanation, and by using the appropriate units in the discussion.
2. Operationally define the concept of temperature gradient as it is used to describe the thermal transport process of conduction.
3. Describe, for each of the heat transfer processes of conduction, convection, and radiation, how the rate of heat flow depends upon isolated factors (e.g. temperature gradient, surface area, etc.).
4. Distinguish between the concepts of <u>thermal energy</u> and <u>heat</u>.

Objectives

After you have completed the content of this part of the module, you should be able to:

1. Describe qualitatively, the variation of skin temperature of the human body at various locations (trunk, legs, head, etc.) compared to the internal (core) temperature as a function of environmental temperature.
2. Utilize the concept of evaporation to evaluate the rate of heat transport.

3. Utilize the concept of conduction, convection, or radiation to evaluate the rate of heat transport (or one of the correlative variables) in a physical situation where any <u>one</u> of these processes is involved.
4. Given a physical system in which more than one of the heat transport processes is possible, distinguish which of these competing mechanisms is likely to be the <u>dominant</u> one under the given set of conditions.

Explore by Thinking: What does your body feel like in different thermal environments?

Explore by Doing: Use your body to sense temperatures and create a subjective temperature scale. Measure the temperatures around your body under various conditions. Examine and measure temperature patterns which occur in simple conductive (hot dog), convective (chilled beaker of water), radiative (flame), and evaporative (wet hands) thermal energy transfer processes.

Learn (Section D) about different ways of measuring temperatures.

Learn (Section E) how the temperature of your body differs from one part to another.

Learn (Section F) how to evaluate the rate at which thermal energy is transferred from one body to another by various (four different) mechanisms, as exemplified by simple, physical systems.

Apply the basic heat transfer laws to simple physical systems (such as a long cylinder which can serve as a model for a human limb) in order to evaluate rates of heat transfer in differing situations.

Develop a graphically represented comparison of subjective and thermistor-measured temperatures.

Calibrate a thermistor.

Apply the conductive heat flow law to your "hot dog" data (exploration) to evaluate tissue conductivity.

Check the reproducibility of body temperature measurements.

2. FUNDAMENTAL ENERGY PROCESSES OF THE HUMAN BODY

Prerequisites

1. Describe, using the appropriate units, the interrelatedness of the concepts of potential energy, kinetic energy, and mechanical power.
2. Calculate the magnitude of each in an example if given an object's mass, its relative height, time required for the work to be completed, and/or its velocity.
3. Distinguish between the terms "thermal energy" and "temperature" by providing a written explanation of what each term represents, by providing a basic example which illustrates your explanation, and by using the appropriate units in the discussion.
4. Utilize the concepts of conduction, convection, radiation, and evaporation to determine the quantity of heat transport in each process in a physical situation involving one or all of the processes.
5. Describe qualitatively, the variation of skin temperature of the human body at various locations (trunk, legs, head, etc.) compared to the internal (core) temperature as a function of environmental temperature.

Objectives

After you have completed the content of this module, you will be able to:

1. Relate the metabolic rate of the body to the calculated work being performed and to the rate of heat transfer. Estimate the efficiency of the body in producing mechanical power in a given situation like running, cycling, or climbing stairs.
2. Describe qualitatively the function of each of the four thermal transport phenomena utilized by the body in regulation of its temperature (conduction, convection, radiation, and evaporation) and outline the environmental conditions required for each of these transport phenomena to act at the body's surface in a maximum and in a minimum capacity relative to the others.
3. Calculate, for a human body in a given situation, the rate of energy produced in mechanical power, and lost through one or all of the four forms of heat transport at its surface, and write a total energy balance expression for the body.
4. Provide values, reasonable and appropriate for the human body, for quantities such as surface areas, skin temperatures, conductivities, etc.

Explore by Thinking: The component of food which enables you to perform activities is not related to quantity in an obvious way. There are paradoxes between the physical and experiential notions of work.

Explore by Doing: How does it feel to do various kinds of work? How does the metal ball with a heating coil inside resemble your working, living body? Observe the way the (ball) simulated body changes its temperature in response to environmental condition changes.

Learn how energy conservation can be used as a guide to describing and evaluating energy management in the body.

Learn how the physical quantities such as work and power relate to human processes.

Learn what metabolic rates are and evaluate how they are balanced by various (four) heat loss mechanisms occurring at the body's surface.

Apply the work-energy theorem, energy conservation, and four basic thermal energy transfer concepts to the problem of evaluating energy management in the human body.

Apply the heat transfer laws to data from heating the simulation body to various temperatures in order to evaluate quantities appearing in those laws. Compare the fractions of total heat lost by different mechanisms.

3. THERMAL REGULATION OF THE HUMAN BODY

Prerequisites

1. Evaluate heat flow in systems involving the four major thermal energy transport mechanisms (conduction, convection, radiation, evaporation).
2. Describe qualitatively the function of each of these four thermal transport mechanisms at the body surface and relate appropriate environmental conditions to the dominance of one or another of these mechanisms with respect to temperature regulation of the body.
3. Write, and use to evalute process energies, the total energy balance equation for a given body in a given environment.

Objectives

After you have completed this module, you will be able to:

1. Qualitatively describe the internal mechanisms (e.g. vascular constriction, countercurrent heat exchange, shivering, etc.) used by the body to regulate its temperature.
2. Utilize a standard surface heat transfer table and the standard heat exchange laws to evaluate the contribution of each of the external (surface) heat exchange mechanisms to the total temperature regulation effort of the body.
3. Recognize and describe the performance of a feedback system which is capable of maintaining a steady system temperature.

Explore by Thinking: How many manners of your body response to heat/cold can you identify?

Explore by Doing: Operate a countercurrent heat exchange system and see what it feels like to regulate the "extremity" temperature of a distant beaker. Do a simple kind of regulation/control exercise with the simulation body.

Learn how countercurrent heat exchange works in general and in your body.

Learn what "feedback" has to do with a (temperature) regulation system.

Learn to evaluate the outcomes of your body's regulation activities by evaluating the <u>partitioning</u> of heat flow among the several possible mechanisms under differing environmental conditions.

Apply the heat flow laws and mechanism partitioning facts to evaluate the rates of heat flow via various mechanisms in a variety of circumstances including: different metabolic rates and different environmental conditions.

Develop a manner of correlating measured "thermal response times" of the simulation body to the effectiveness of regulation schemes having different "regulation response times".

III. Guide to the Text Materials

Certain discrepancies among the data in existing pedagogical literature have become apparent to us in researching the content of these modules. It is possible that incomplete reporting of conditions has concealed the reasons for these; but it is possible that the data themselves are not entirely reliable.

It is beyond the scope of the present project to make what would appear to be a useful critical survey of these data. Some caution is, therefore, advisable in taking these data too literally.

It is within the scope of this project, however, to assemble a hopefully self-consistent and comprehensive picture of the thermal energy economy of the body. An overview of the modular content is now presented to aid in forging that self-consistent view and to serve, especially, as a tutorial for faculty, whether they intend to teach with these materials or merely wish to use this overview as a convenient resource for learning something about body thermo-physics.

There are a number of concise, applied physiology books available to provide resource material. Two of these which are available are:

Physiological Basis of Human Performance;

Benjamin Ricci, Lea and Febiger, 1967; Philadelphia, PA.

Physics in Biology and Medicine;

Paul Davidovits, Prentice Hall, 1975; Englewood Cliffs, NJ.

The picture of the human body's thermal response that emerges is that it is a marvel of adaptability. The body's core temperature must, for biochemical reasons, remain nearly constant. The various body responses serve to drive the surface temperature up and down over a wide range in order to regulate the outward energy flow (heat) which then results in the maintenance of "core" temperature constant to within about 1°C over the course of one entire day.

This is somewhat remarkable considering that the power output, in terms of external work, is accompanied by, typically, four or five times that amount of internal dissipation in the form of thermal energy which must be removed. (Daily total energy turnover is typically 8 Megajoules!) This power is in addition to a modest "base line" level needed to maintain vital body functions. In general the power developed inside the body is called the metabolic rate (MR) and is best quoted per square meter of body surface area. The minimum MR required for vital function is called the basal MR (or BMR) and is the lowest of a whole range of MR values which depend upon activity. These range from:

40-50 watts/m^2 (sleeping; wakeful inactivity) to 700 watts/m^2 (running)

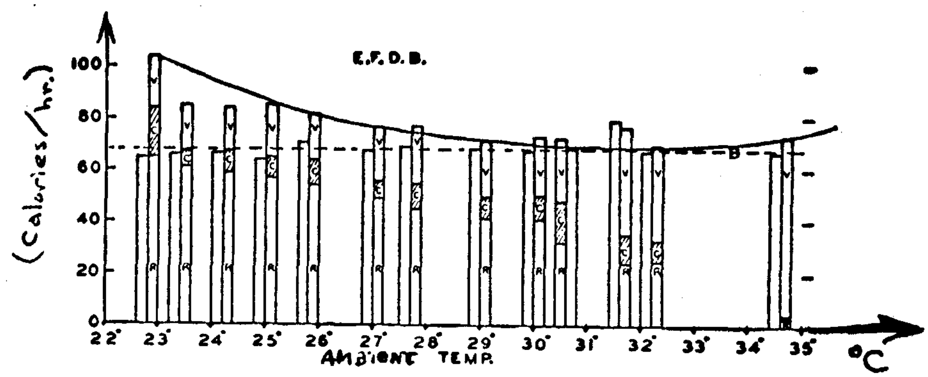
The megajoule is a useful unit to use when treating physiological energies. (See above, 8 megajoules = daily energy diet.) It is a good idea to keep these few figures in mind when contemplating the energy management of the body or when discussing these matters. A more complete table than appears in module II (Fundamentals), page 23, is given below; discrepant values from the literature have been stated consecutively:

Activity	Average Adult Metabolic Rate per Area (watts/m^2)	Multiple of BMR
Sleeping	40, 41	1.00
Lying awake	46	1.14
Sitting at rest	43, 58	1.06, 1.43
Standing	50, 70	1.23, 1.73
Walking (1.2 m/sec)	108	2.67
Walking (1.4 m/sec)	162	4.00
Moderate work	174	4.30
Walking downstairs	237	5.8
Bicycling	290	7.2
Shivering	290	7.2
Walking upstairs	616	15.2
Running	700	17.3

Table 1: Comprehensive list of metabolic rates for various human activities.

In order to illustrate what sort analyses can be accomplished using the material of this modular cluster, we here calculate the way energy loss is partitioned among various mechanisms at two different ambient temperatures. In the course of this calculation we shall also develop a comprehensive way of looking at thermal energy losses from the body. This latter development will assume the form of a table useful for evaluating how various parts of the body contribute their share of the total energy loss.

This calculation starts by anticipating that radiation and evaporation are going to be the principle means of thermal energy transfer from the body to its environment. This well known physiological phenomenon is illustrated in the following graph.



Columns, to left = thermal energy production

Columns, to right = heat elimination
V = vaporization
C = convection
R = radiation

Figure 3: Thermal energy production and loss in a nude male in the basal condition at various ambient temperatures. (After DuBois, Bull. N.Y. Acad. Med., 1939, Ser. 2, 15, 143-73).

We will now employ the energy exchange laws and other, physiological data drawn from the modules in this cluster to elucidate the conditions which accompany these energy transfers summarized in the graph of Figure 3.

First we evaluate the energy exchanges when the ambient temperature is T = 20°C. The nude subject has skin temperatures at four selected body locations which are summarized for various environmental temperatures in Table E5 on page 15 of module I (Thermometry). In order to apply the energy transfer laws, then, we must do separate evaluations at each of the four major body areas because they, as can be seen from the table, are generally at temperatures different from one another for any given ambient temperature. These start with a subdivision of total body area into fractional areas in the manner of Figure 4.

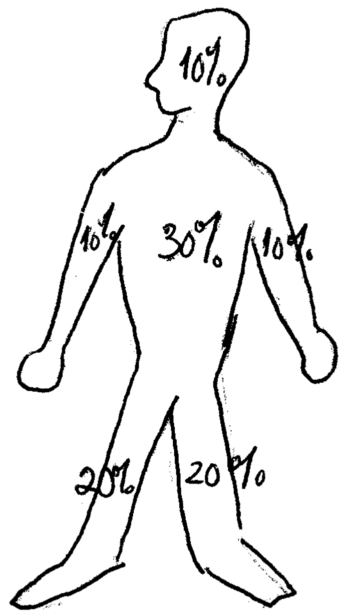


Figure 4: Area subdivisions of the human body.

The values for each of these parts are:

Head	=	10%
Upper body (arms)	=	20%
Lower body (legs)	=	40%
Trunk (torso)	=	30%

Based upon this partitioning, one can now calculate the radiative heat exchange between each region of this body and a T = 20°C (293°k) environment. We select radiation first because Figure 3 appears to predict that this will be the dominant mechanism at this ambient temperature.

<u>Net</u> heat output from

head; @ T = 29°C (302°k); h_R = 5.4 watts/m^2

arms; @ T = 29°C (302°k); h_R = 10 watts/m^2

legs; @ T = 27°C (300°k); h_R = 17 watts/m^2

torso; @ T = 31°C (304°k); h_R = 22 watts/m^2

These net radiative losses total to 44 watts/m^2, which just equals the average BMR. Beyond this, 12 watts/m^2 of thermal energy is lost to the body by means of vaporization of insensate (inperceptible) perspiration and 18 watts/m^2 by convection/conduction. The former is from a value of perspiration fixed at 10 ml/sec. for all environmental temperatures $T_a < 30°C$. The latter is calculated from data on a graph in Figure G2 of module II (Fundamentals).

The manner of these calculations will be summarized shortly. At this point it is well to note that these calculations agree well with reasonable extrapolations of the data of the experimental findings reported in the graph of Figure 3. Also in accord with results there, the energy output from the body under these conditions exceeds the input at the normal BMR. Students can find this result from an application of equation D.2 in module II (Fundamentals).

A question of interest is, at what higher temperature does the BMR just match the energy losses. By definition, this temperature is called the critical temperature of the organism, and is a measure of its adaptability to cold. For humans, as shown on the graph of Figure 3, this temperature is about $T_a = 30°C$. The results of an evaluation, similar to the one done above for $T_a = 20°C$, are presented along with the previous results in the following table.

	Region:	Head	Arms	Legs	Torso	Fractional Loss
	Fractional area :	10%	20%	40%	30%	
	Mechanism					
watts/m^2	Radiation :	5.4/2.6	10/5.2	17/6.5	22/7.8	59%/54%
watts/m^2	Evaporation :	1.2	2.4	4.8	3.6	16%/29%
watts/m^2	Convection :	1.8/0.8	3.6/1.6	5.6/3.0	6.6/2.4	24%/17%
	Fractional loss :	10%/11%	19%/22%	33%/34%	38%/33%	

Table 2: Partitioned thermal energy losses at two ambient temperatures 20°C/30°C, calculated from the basic heat exchange laws; thermal energy exchange units are watts/m^2.

The total energy loss at this temperature thus calculated is 40.9 watts/m^2, just about equal to the BMR, as anticipated. At this point, the body regulatory mechanisms are just able to regulate core temperature without extraordinary measures (e.g. shivering). Truly, nude Man is a tropical beast!

To complete the ground work for a neat summary of energy losses, we need only yet linearize the radiation heat exchange law. Because $\Delta T << T_{avg}$ over the range of ordinary physical variability (i.e., ΔT = 40°C - 0°C and $T_{avg} \doteq 300°k$), one has for the radiation exchange law expressed in equation G.11 of module II (Fundamentals) the following approximation:

$$h_R = (7.0 \text{ watts/m}^2 - °C)\ (T_{body} - T_{walls})$$

Now we can make a table giving rates of heat loss by various heat exchange mechanisms on a <u>per degree temperature difference</u> basis. This is very handy. Included also are the evaporation loss rates which are not heat (i.e., do not depend upon temperature differences between the body and the environment) but do occur at, typically, three different rates which are in response to different amounts of activity.

Process	Rate (watts/m^2-C°)	Head	Arms	Per Region (watts/m^2-C°) Legs	Torso
Radiation	7.0	0.7	1.4	2.8	2.1
Convection (natural)	2	0.2	0.4	0.8	0.6
Convection (2.4 m/sec ≃ 5 mph)	20	2.0	4.0	8.0	6.0
Evaporation* (normal, insensible, persistent)	12	1.2	2.4	4.8	3.6
Evaporation* (heavy sweating, hours only)	190	19.0	38.0	76	57
Evaporation* (heavy sweating, minutes only)	1200	120	240	48	360

Table 3: Thermal energy loss rates per degree body/ambient difference, according to regions.

*These rates are watts/m^2 and do <u>not</u> depend upon temperature difference.

At higher ambient temperatures, evaporation becomes the dominant thermal energy loss process. When the ambient temperature exceeds the body core temperature, evaporation becomes the only thermal energy loss mechanism. The reason for this is clear; evaporation alone is not a heat process. Its ability to transfer thermal energy does not depend upon the temperature difference between the two objects involved in the energy swap.

The preceding calculations, the results of which appear in Table 3, are at the heart of the cluster objectives, and much of the content material points to them, although demands for such calculations per se from the students in problems are confined to the final (module III, Regulation) module. As the instructor you may see fit to introduce this accounting scheme at other points, or perhaps use it yourself.

There are a number of additional points about the content that warrant mention. First, carefully note the restriction of the word heat to that process of (thermal) energy exchange which happens by virtue of the temperature difference between two objects. This distinction is frequently not done in physics texts, where heat or heat energy is often used to describe internal, thermal energy. Heat (like work) is a process, not a state variable. And the First Law of Thermodynamics is a generalization of the work/energy theorem, not a statement of the conservation of energy as it is often framed. This distinction is made throughout not out of pedantic compulsion to thermodynamic rigor, but out of conviction that very pratical matters, such as the meaning of efficiency, can only be fully understood when it is viewed as a process related quantity. Incidentally, be forewarned that the physiological literature is no less careless in these matters than physics textbooks.

The units of energy and power used are joules and watts per square meter, respectively. (Many physiology texts use Calories/hr. 1 Calorie = 1000 calories and 1 Calorie/hr. = 1.16 watts.) This decision was made in the interests of bringing the physiology one step closer to the physics being learned in the typical course of which these modules are likely to be a part. (And it might be added, into contact with the other parts of the world of students' experience. For example, how does a light bulb compare with a body as a source of thermal energy?) Moreover, we are led to understand that the "megajoule" is coming into fashion in discussing such things as diet, and we have no desire to resist this trend. (8 megajoules ≐ 2000 Calories). Incidentally, all quantities are evaluated on a per square meter basis because the source energy (metabolic rates) apparently scale in proportion to surface area in terms of their variance across a range of body sizes for a given sex.

A regrettable lapse was made in presenting values for thermal conductivity coefficients, e.g., Table F1, module I (Thermometry), and Table G6, module II (Fundamentals). To be both consistent with the rest of the material and practical at the same time we should have chosen 1 watt cm/m^2°C = 10^4 watt/cm°C. In this mixed unit, the conductivity of (unperfused) tissue has a value of about 15 watt cm/m^2°C, and the temperature gradients needed for the evaluation of the conductive flow can be conveniently expressed in °C/cm.

A good deal of searching* was done before realizing that a comprehensive flow chart showing the heirarchy of energy transformations from food to heat/work was lacking in the literature. Accordingly, the chart on the bottom of page 11, module II (Fundamentals) should be a handy adjunct. Processes are listed there in lower case letters to distinguish them from "state variables" listed in capital letters.

---

*Apparently not enough searching; a useful but in my opinion still not as comprehensive diagram appears in the 1973 version of "Physiology and Biophysics," Volume III, Ruch and Patton, pg. 89.

Students are frequently bewildered by the apparent paradox between the physical definition of work and the physiological sensation of "work". We have tried to provoke a confrontation with this paradox in module II (Fundamentals), section E: Mechanical Power, and in the Exploration Activities in that module. However, it occurs to us now that we did not aid the cause of resolution by omitting a vector diagram to show what d_F (component of the displacement along the force vector) is, nor by failing to point out that the extreme case of "zero efficiency work" makes transparent how such paradoxical behavior is already accounted for in the physical theory.

A log-log graphical plot of the maximum power output data in Table E.1 of module II (Fundamentals) will assist in solving some of the problems by appropriate interpolation. This tactic is not obvious to students. This plot is linear over three decades in task duration time.

In the section G: Rate of Heat Loss of module II (Fundamentals), the linearized approximate form for the radiative heat transfer law, valid over the range of physiologically important temperatures (0°C → 40°C) and which was introduced earlier in this guide, does not appear. It greatly simplifies radiative transfer calculations and ought to be presented to students.

It has been pointed out to us that the explanation of the operating principles of the counter-current heat exchange in module III (Regulation) section D is too sketchy. A considerable amount of intuition about thermal conductivity is indeed expected on the part of the student. This criticism can be leveled at the other topics in this module III as well, since it was intended as a descriptive introduction to only thermal regulation activities of the body, and expects competence of the students to do heat transfer calculations.

Another deficiency is that only Table D.1 presents explicit information on partitioning of thermal energy loss among the various mechanisms and is empirical rather than analytic. In this regard the tables presented earlier in this section of the guide would probably be valuable additions and better provide resources for the student to achieve the learning objective (2.) of module III, i.e., evaluate the relative contribution of each mechanism of thermal energy exchange. In retrospect, it is apparent that this was a serious omission.

Note that that part of the discussion of feedback mechanisms dealing with the concept of thermal response time in the feedback loop is <u>not</u> part of the discussion in the Invention part of the text, but is relegated to the Exploration and Applications part. This means that it is introduced in an experimental context, and is restricted to this phenomenological perspective. For a more complete discussion see, for example, R. K. Hobbie.

IV. Guide to the Laboratory Exercises

A. General

The lab exercises are divided into two logical parts: (1) Those providing experiences and data for organization around the physical laws and/or explanations of the invention phase; (2) those requiring application or extension of those physical laws.

Group (1) experiments appear in the Exploration Activity sections and are designed to be technically and conceptually simple. It is felt that they can be done, by the average student, unsupervised. This belief has been tested and found to be generally true provided that certain requirements of the laboratory environment are respected.

(1) Simplicity: Keep the area uncluttered and have adequate space work.

(2) Durability: This is obvious, but students do find ways to subvert honest effort here. Keep spare parts for breakable items and check them regularly.

(3) Clarity: Label everything that must be touched by the students. Keep the labels simple so that they may be decoded at a glance. Also, I strongly recommend that you post step-by-step instructions, but in <u>very abbreviated</u> (never try to simply copy the "instructions" in the text description) form. If you've ever been to a "hands on" science museum like Frank Oppenheimer's San Francisco Exploratorium, then you may have noticed as I have how "untouched" are the experiments with complicated instructions. Use <u>large lettering</u> and <u>space lines well</u>. Very often students will skip over lines that are tightly spaced; remember that they are looking from afar, have their hands full, and can't keep their finger on a line of text to mark their place.

You should probably plan to spend some time watching directly (better yet watching video tapes) of students trying to handle your apparti by themselves. You'll probably be amazed at where the troublesome spots are. This need be a one-time-only effort. Once things are working smoothly, then the experiments run themselves. If you uncover troubles which are persistent and fresh, let us know so that we may inform others. Our own experiences are summarized in the comments on individual exercises which follow this general discussion.

Finally, a word about the Group (2) experiments which appear in the Applications sections. They are more elaborate. They need supervision and ought to be done with the warm body of an instructor nearby. You may wish to label parts and provide rudimentary instructions. Moreover, there are far more experiments than any individual student will want to handle. We suggest that you select which are to be done with some circumspection.

B(1) Specifics of Module 1: Thermometry.

Any introduction to thermometry, it seems, ought to emphasize the arbitrariness of the temperature scale. In this respect, the applications exercise on thermistor calibration, we feel, is quite important. In the Group (1) explorations students are not given a calibrated read out device. We used a bridge circuit (see Equipment Notes, next section) and drove a microammeter with the out-of-balance signal. Some students are very uncomfortable measuring temperatures in microampere units.

Further, we saw some pedagogical advantages in further disabusing the students of their prejudices about how thermometers and temperature scales ought to be. Accordingly we experimented with arranging the bridge balance condition such that <u>increasing</u> temperatures produced <u>diminishing</u> values of imbalance current. Thus the thermometer was especially perverse, not only refusing to reveal its stripe as a Fahrenheit or Celsius instrument, but also working backwards!

One of the chief advantages of this was realized in the body temperature measurements before and after exercise where students contentedly watched the current readings increase at most parts of their body surface after exercise as compared with before. This of course signaled an (unexpected) decrease in temperature, and is widely reported under many conditions for those (uncovered) areas where sweating/cooling dominates the effect of increased blood flow to the surface. Rest assured that if the thermistor circuits had not been rigged perversely and these temperatures obviously been found to decrease, that a sizable percentage of students would have struggled to repeat experiments in a futile effort to make the results come out "right". There is a lesson in scientific fidelity here somewhere, and perverse thermistors have proved to be as good as chastity belts.

The hot dog experiment was included even though its merits are mixed. In particular, we were never able to achieve a steady state in a reasonable amount of time without cooking one end of the hot dog. The transient state is not uninteresting and raises some pertinent questions in students' minds. However, as a semi-quantitative demonstration of the (steady-state) heat conduction law, this does not seem to work well. One other reason for retaining it, however, lies in the obvious similarity of hot dog to body tissue.

The convection experiments using the nested beakers show a dramatic difference between natural and forced convection. One problem is getting beakers the right size to assure a relaxation time of 15-20 minutes, not a trivial task for the natural convection situation. Beyond this time students (understandably) lose patience. We have also experimented with doing four different arrangements instead of two, where the additional two are done with hot water in the bottom beaker, and stirred/unstirred room temperature water on top. Here the natural convection is more vigorous due to the density inversion.

The first experiment in the Applications Section, Group (2), we found a pleasant surprise. The students seemed to enjoy, and consistently succeeded in, discovering the fact that their hot/cold responses were quite different, one being differential and the other being directly responsive to the stimuli. The one inch diameter aluminum ball, instrumented with a thermistor, which was used to measure the relative temperatures of the three baths had a response pattern not unlike that of the cold sensor in the hand. The time constants, too, were similar. Typical results are presented in the following student-made graph.

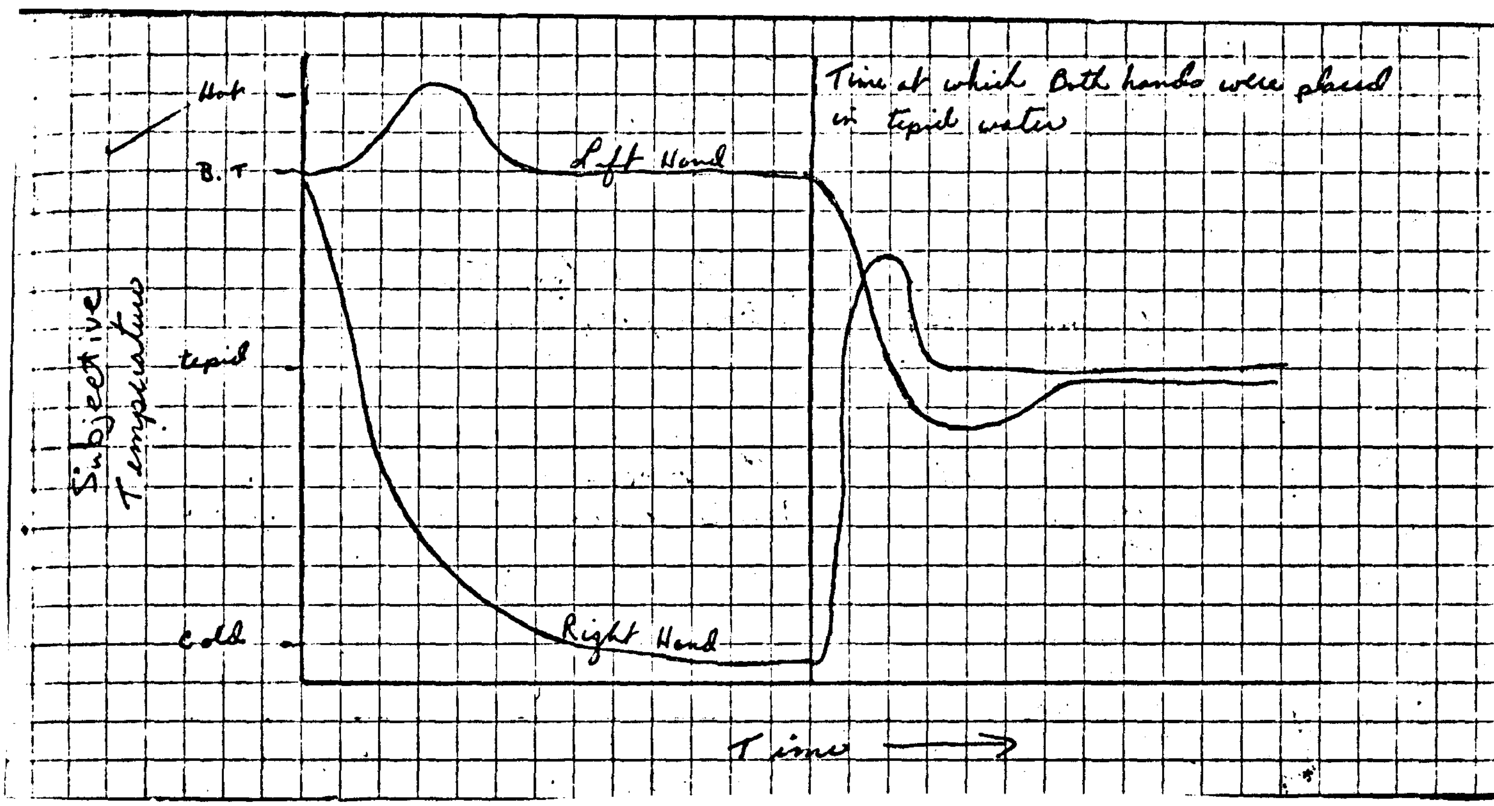


Figure 5: Student's results of subjective temperature versus time elapsed after plunging one hand (left) in hot and the other hand (right) in cold water baths. Later, each was placed in a (common) tepid bath. (After Module 1: Thermometry; Applications Section.)

Again, the hot dog experiment has its problems. The requirement of the applications exercise (3), namely that estimates of energy input from the bulb be made, do <u>not</u> simplify matters. In fact a numerical integration of the temperature rises throughout the hot dog as a function of time, together with an assumption about heat capacity of the hot dog contents, do allow one to evaluate, approximately, the input power as a function of time. However, this is a rather lengthy procedure requiring considerable reasoning skill to follow the logic thereof. Consequently it is, perhaps, ill-advised to do the full analysis which is demanded here.

B(2) Specifics of Module 2: Fundamentals

Depending upon the physical condition of the participant, you may need more than one shelf full of books to produce a noticeable effect.

Students tend to be impatient with heating the ball, and are prone to turn up the current until the system "smokes". Take precautions to fix the range over which they can adjust the current and do not underestimate their cleverness at circumventing traps you have set to control their lust for the destruction of lab equipment. In the applications section a <u>reasonable</u> power level is requested. Don't leave this to students' imagination as the test suggests.

Although it does not say so, the data of exercise #2 of the applications section is easiest to analyze when a temperature level already used in exercise #1 is repeated, this time with air movement from the fan, and the <u>difference</u> in power required to maintain the identical temperature in both cases is evaluated as that due to additional convection.

Inexpensive and appropriate wind velocity indicators are available (see

Equipment Section following) and should be used to establish the air velocity in each case.

B(3) Specifics of Module (3): Regulation

A suitable countercurrent heat exchanger can be fabricated using a standard chemistry lab distillation condensor, with PVC tubing bypass. (See Equipment Section following.) It is useful to have a thermistor stuck right in the effluent tube; however, it is also nice to have a second thermistor in the "extremity" flask, right at the outflow port. The temperature of either or both may be monitored.

The secrets of making this exchanger work are:

- run water slowly
- keep extremity in an ice bath and use purely hot tap water
- keep the whole apparatus in a sink so that nothing need be moved during the course of a run.

Using this apparatus and this methodology we were able to obtain reproducible temperature swings between 40°C (flow shunted outside) and 44°C (flow directed inside) at the effluent using a volume flow rate of between one and two milliliters per second.

For the calibration of the power source used with the simulation body, it is useful to start with the bare ball in a quiet (of wind currents) room and establish that power needed to maintain physiological temperature (37°C). This should be labelled "wakeful rest". (We used labels pasted right on the Variac.) Then, after computing the ratios of physiological "wakeful rest" (B)MR to other MR's, we labelled the other appropriate Variac settings with descriptive titles (e.g., mild work, sleep, etc. Don't forget "death" at the zero current position).

The most important new concept in the applications section, Group (2) experiments, is the concept of thermal response time and its effect upon the behavior of the feedback system. Particularly troublesome is exercise #3, which is essential for correlating response time with feedback behavior. Here are the rudiments of the problem:

- In order to make the simulation "game" as close as possible to the body's regulation task, one of the system conditions which regulates the heat losses ought to be the independent variable, and the objective of the simulation exercise ought to be to restore the ball temperature to a previously determined "normal" value after a jump is made in the level of the dissipation (source) energy inputted.
- On the other hand, change in the system variable generally entails a change in the ball's relaxation time (e.g. change in air velocity). This compromises any comparison of the system behaviors based upon variation of the ratio of (feedback sampling)/(relaxation) times. Such a comparison implies that there is a <u>definite</u> relaxation time for each approach to equilibrium in which the control (independent) variable is the system factor (e.g. air velocity).
- One may limit the change in relaxation time by limiting the range over which the system variable must be changed in the course of restoring the ball to the normal temperature. However, attendant to this limitation of range is a limitation to the scope of input energy jump which the environmental variable can accomodate.

Here are two ways to solve this problem:

- Change the strategy of simulation by allowing the input energy to be the independent variable. This belies the real life system.
- Be judicious in choosing the initial conditions and the target (i.e., normal) temperature so that both conditions ("fixed" relaxation time and sufficient "scope" to accomodate the input energy level jump) are simultaneously satisfied.

This latter strategy has been implemented by carefully studying the relaxation times and equilibrium temperatures of a simulation body (ball) for a variety of (convective) air flow velocities and (dissipative) input energy levels. A table of such typical values appears below. Following that table is a set of graphs showing the time behavior of the ball temperature in a typical set of relaxation experiments (a); and in three different feedback experiments (b), as follows:

- fixed input energy and air velocity (steady-state)
- restoration of ball temperature using the monitoring (i.e., sampling) time interval short compared to the relaxation time
- same as above but with sampling interval long compared to the relaxation time.

Equilibrium Temperature (microamperes)	Air Velocity m/sec	Relaxation Time (minutes)	Heating Current (amp.)
4.2 ± .1	2.91 ± .05	2.7 ± .1	0
6.5 ± .1	2.91 ± .05	2.5 ± .3	1.0
17.9 ± .1	2.95 ± .05	2.2 ± .2	1.7
20.0 ± .1	2.28 ± .05	2.6 ± .1	1.7
4.0 ± .1	1.48 ± .03	3.2 ± .1	0
23.1 ± .1	1.74 ± .20	3.15 ± .1	1.7
8.1 ± .1	1.18 ± .10	3.6 ± .1	1.0
26.2 ± .1	1.25 ± .10	3.7 ± .1	1.7
2.3 ± .1	1.35 ± .15	3.65 ± .1	0

Table 4: Conditions at equilibrium for a typical simulation body cooled principally by forced (air) convection from a fan located at varying distances.

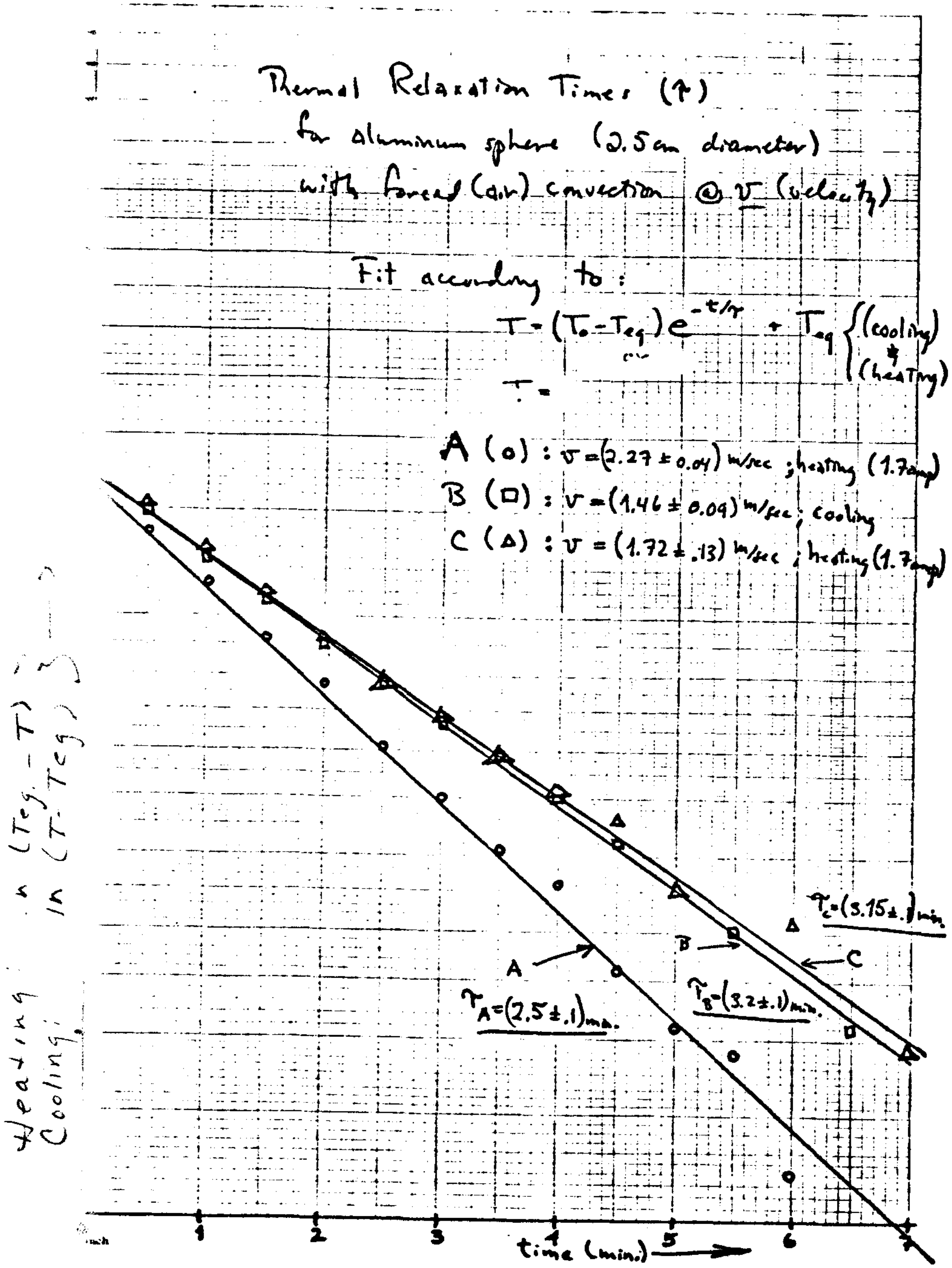


Figure 6(a): **Graphs of typical relaxation experiments, time course of** temperature subsequent to an input energy "jump".

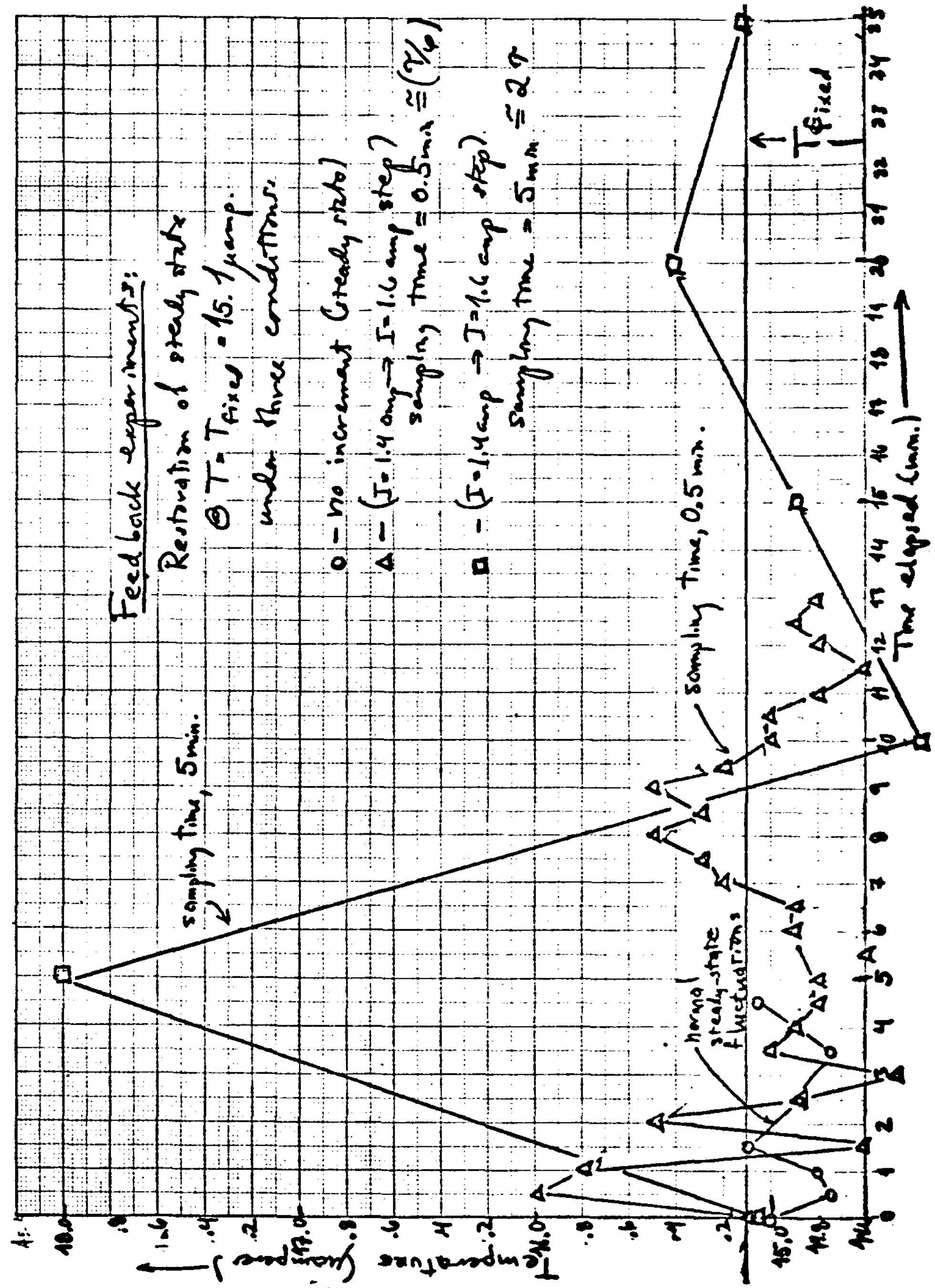


Figure 6(b): **Graphs of feedback experiments time course of temperature under** conditions indicated.

You will notice that in the feedback experiment, an increment in current has been chosen (i.e., input energy jump) large enough to cause a readable shift in the ball temperature but small enough so that a shift in fan position can accommodate the additional heat burden and restore the ball to the equilibrium (target) temperature. The value of the relaxation times appropriate to the "before" and "after" velocities can be interpolated from those given in the table. These are 3.7 min. and 2.8 min., respectively. They are sufficiently close so that the sampling times in each of the two feedback cases presented are clearly less than and greater than, respectively, the range of relaxation times involved in the approach to equilibrium.

It is important for students doing the feedback experiments to have a proper sense of what constitutes arrival at the target temperature. One of the three feedback experiment graphs depicts the typical steady-state temperature fluctuations. A range should be selected, based upon the size of these fluctuations, which then constitutes a target "window;" the goal of the feedback experiments should be to bring the ball temperature within this window about the average target temperature value.

There should also be some "ground rules" about the adjustments of air velocity (via fan positioning) in the procedure for the approach to normal temperature. At a time spacing equal to the appropriate monitor (or sampling) time, the student is to then (and only then) check the temperature and make an adjustment whenever it does not fall within the target temperature window. This must be an if and only if situation; otherwise the clever student can always defeat the oscillatory effect experienced when the sampling time is short compared to the relaxation time (and the system is therefore "over compensated"). The graph clearly shows this characteristic behavior.

In summary, exercise #3 in the applications section as it now appears seems to be inadequate and requires some supplementary information drawn from the previous discussion here. In any case, certain restrictions must be made upon the values of current jumps, current levels, and fan positions to use in order to obviate the difficulties described while maintaining the realistic analogy between the simulation experiment and the real-life system as envisioned in the original formulation of this exercise.

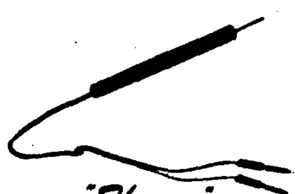
V. Equipment Notes

There are several possibilities for acquiring capability to measure body surface temperatures. The one which we used and found satisfactory is the fourth of these.

Most mercury-and-glass laboratory thermometers have a high thermal inertia. These thermometers must be placed in contact with a surface for an extended period of time before thermal equilibrium occurs. While in contact with the skin's surface, these thermometers interfere with normal heat losses and therefore measurement should be made with a low inertia thermometer. Several suggestions appear below.

1. Inexpensive Electric Thermometer. Several models are now available from scienfitif equipment dealers. A most reasonable and acceptable thermometer is sold by Basic Science Industries, 214 Donald Terrace, Glenview, IL 60025, price, approximately $40.00.

2. Electric Sensor. If you have a VTVM or a multimeter, the device described below will provide acceptable readings.



"Thermy" Thermotester

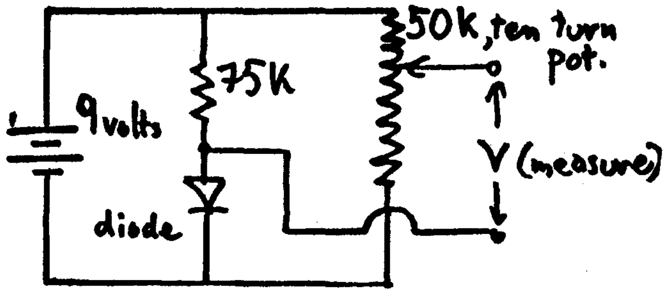
Indicates in seconds whether the temperature of a component is too hot or too cold. This electronic Thermotester is speedy, accurate and durable. Permits access to areas that ordinary thermometers cannot reach. Gives instant readings upon physical contact, when used in conjunction with a VTVM or Multitester. A simple translating scale is provided to convert meter readings into F. or C. Range, from -60° to 400° F. or -50° to 200° C. With 42" leads and case. Shpg Wt, 12 lbs

Cat. No. Q 5028 .... $14.95

OUR TERMS: ALL PRICES NET, F. O. B. PHILA. MINIMUM ORDERS: U. S. $5.00 (OPEN ACCOUNT, $10.00) - CANADA $15.00

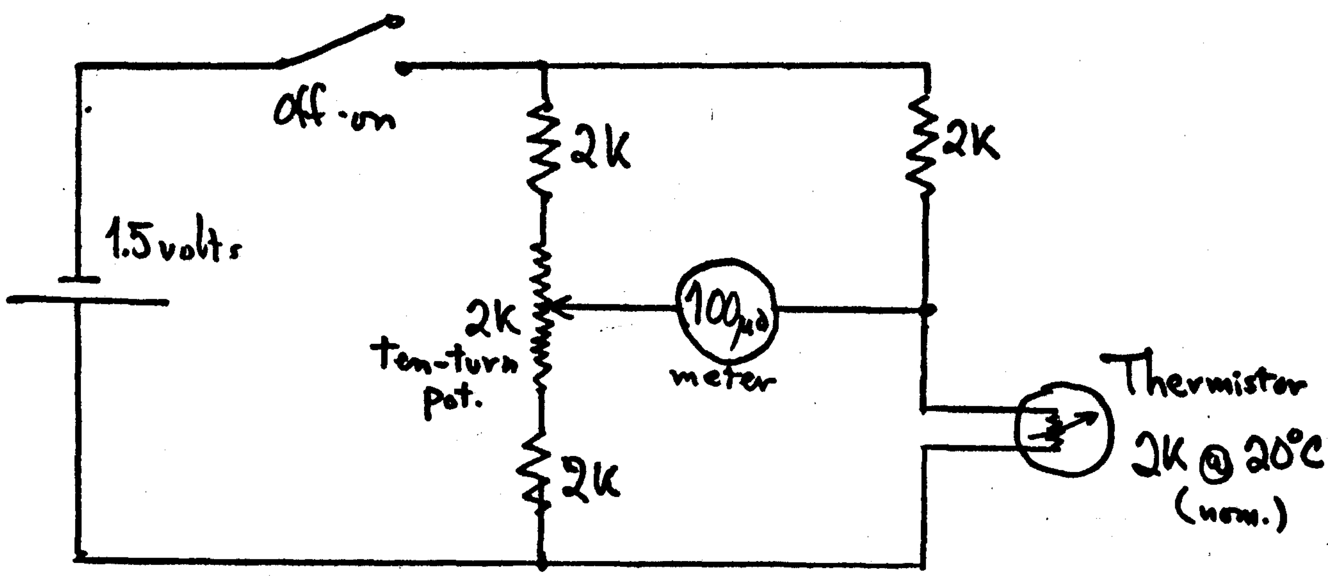
HERBACH & RADEMAN, INC.
401 EAST ERIE AVENUE, PHILADELPHIA, PA. 19134

3. Diode Thermometer. Modern miniature diodes provide the basis for sensitive temperature measurement. The circuit below can be used for calibrating a forward biased germanium diode. A sensitive voltmeter such as a Heathkit digital voltmeter should be used, and small diodes will provide a fast response time.



4. Thermistor Plus Bridge Circuit. A very small, pill-shaped thermistor (Fenwall FB32J1, 2K nominal resistance at 20°C) was fabricated into a probe by encapsulation in thermally conducting epoxy with the leads sealed in teflon tubing. A suitable epoxy is made by Emerson and Cuming, Canton, Massachusetts (Stycast 2850 FT); but there are a number of others available; consult a radio supply catalogue, for example.

The circuit used is depicted below in schematic form:



The "simulation" body was constructed from 10 turns of #28 Nichrome wire (total resistance about 0.6 ohm), wound around a piece of (1.2 mm O.D.) teflon tubing, back through which the copper leads from the coil were drawn.

This entire assembly was epoxied and then inserted into a hole drilled into a 1" aluminum ball (available from CENCO as an aluminum pendulum bob). It was found that this had a thermal response time approximating that of the human hand in a conduction-dominated situation (both inserted into a water bath). (The thermal response time in air is generally larger and varies over a considerable range depending upon environmental conditions, e.g. air velocity, as is discussed in the previous section.) Further, a small thermistor (see previous description) of nominal resistance 2K @ 20°C was epoxied to the surface and crowned with an insulating "cap" of rubber-like mastic. The whole apparatus is depicted in the next figure.

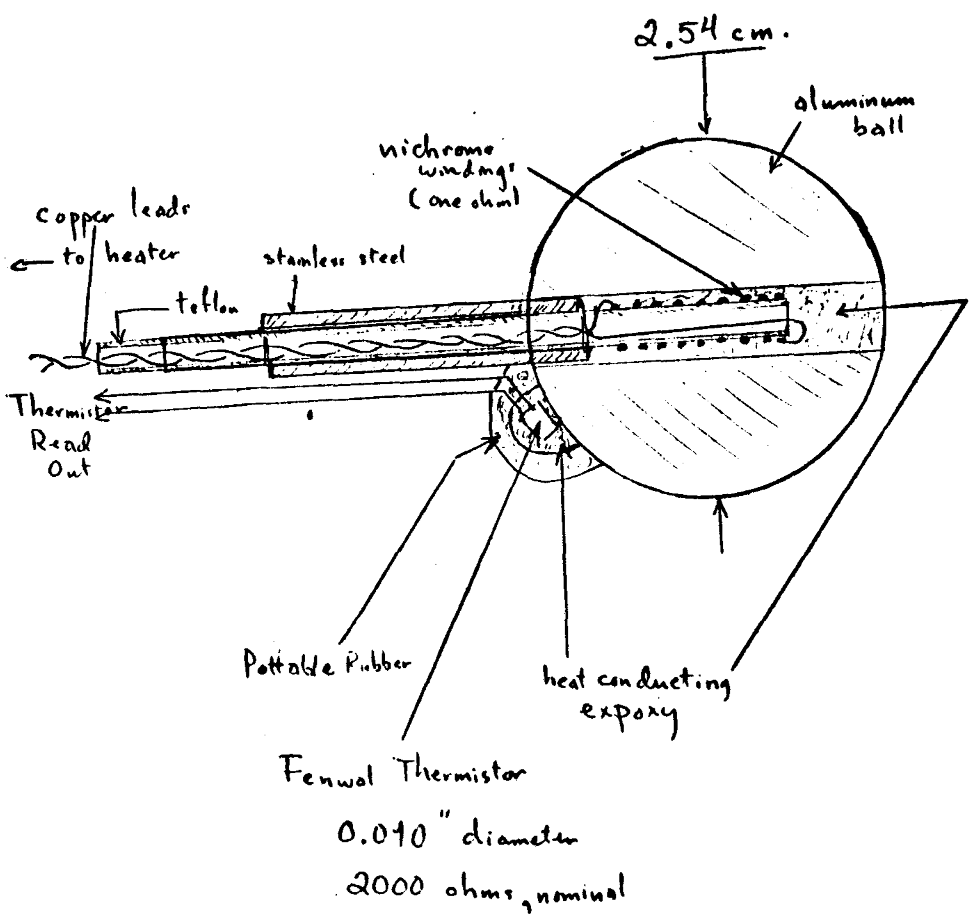


Figure 7: Simulated body with electrical energy source and temperature instrumentation.

A suitable, relatively inexpensive, air velocity meter is manufactured by Dywer Instruments, Inc., Michigan City, Indiana. It is of a type used by yachtsmen to measure wind velocity, is hand held, direct reading, and very simple in design. (A little plastic ball rides vertically in a venturi tube.)

The countercurrent heat exchanger was fabricated from an ordinary chemistry-lab distillation condenser with tygon tubing for the shunts, and hermetically-sealed thermistors stuck into the (extremity) flask and at the output end. The successful operation of this model is described in Section IV, part B(3), the guide to the experiments elsewhere in this document.